Terrestrial gross and net primary production (GPP/NPP) global data set

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Scientific rational and importance of measurement and expected end uses

Global warming induced by dramatically increased atmospheric green-house-gases, especially CO_2, from human activities, such as combustion of fossil fuel and deforestation, has become a global environmental concern. There is now substantial evidence to show that the oceans and biosphere, especially terrestrial ecosystems, currently plays a major role in reducing the rate of the atmospheric CO_2 increase. NPP is the first step to quantifying the amount of carbon fixed by plants from atmosphere and accumulated as biomass. Continuous and accurate measurements of terrestrial NPP at the global scale can be achieved only by using remotely sensed satellite data. The MODIS GPP/NPP data set operationally provides global weekly GPP and annual NPP at 1-km for vegetated areas, which is valuable in ascertaining the role of land vegetation in mitigation of global warming.

Besides being an important component of the global carbon cycle, MODIS NPP is useful both to measure the changes in environment, such as desertification, deforestation, disturbances (e.g., fire and insect outbreak), and the impacts of pollution and climate change; and to evaluate ecosystem's status and services, such as ecosystem health, habitat and wildlife, and ecological footprint. Because NPP can reflect the comprehensive environmental status from both vegetation and the near surface atmosphere, the repeated and consistent MODIS NPP is superior to the traditionally widely used remote sensed Normalized Difference Vegetation Index (NDVI) in the evaluation of environmental changes.

MODIS NPP is also very useful product for land management, renewable natural resource estimations. For example, public land managers can use the data to reevaluate grazing schedules instead of setting a fixed schedule because interannual weather variability can cause vegetation development to vary widely. Some studies have shown that MODIS GPP and NPP can be used to quantify the production of grasses, crops and forests. For example, it has been found that MODIS GPP agrees well with field-observed herbaceous biomass for a grassland in North Dakota, and it is strongly related to wheat yield for a cropland in Montana. For the forests in the Mid-Atlantic region of the U.S., the regional mean of MODIS NPP is very close to the mean estimated from Forest Inventory and Analysis (FIA) data.

With continuous improvements of the data set's accuracy and more people getting to know it, in the future, the scope of applications of MODIS GPP/NPP may be beyond these listed above, and it will become one of most important scientific and societal data sets.

In one words, MODIS weekly GPP and annual NPP data are valuable for the carbon budget, environmental policy analysis, evaluation of ecosystem, land management, agricultural economics, and monitoring of biosphere change. With all these applications, these data can partly answer the question that "How is the Earth changing, and what are the consequences for life on Earth?", a question that NASA aims to answer.

Scientific requirements for the measurement

The paper by Nemani et al. (2003), published on Science, clearly demonstrated the requirements of MODIS GPP/NPP data set. Using the MODIS NPP algorithm and remotely sensed data from AVHRR sensor, they found that global NPP increased from 1982 to 1999, especially for tropical regions. The Amazon rain forest accounted for 42% of the global increase in NPP. Because NDVI has saturation problems for dense rain forests, it is impossible to obtain such promising findings without remotely sensed NPP.

MODIS NPP is the highest level (level 4) land product and is generated with inputs from other relatively low level products. Therefore, its accuracy and precision are largely dependent on these inputs. As a result, the uncertainties from all upstream inputs and the algorithm itself can introduce uncertainties to MODIS NPP. A more detailed discussion on this issue is in the next section.

The global MODIS NPP data set will have 1-km spatial resolution and an 8-day interval, because 1-km is appropriate for those uses at both local and regional level, and an 8-day time period will allow for filtering out of daily noise while retaining important information on phenology and abrupt environmental changes.

On the global scale, El Niño and South Oscillation (ENSO) is the cause of the largest interannual variability of weather patterns. ENSO has a three to six year return interval, and hence the length of the GPP/NPP record should be at least 6 years. Currently, analyses of the trend of environmental changes have received more interest because people are concerned with the consequences of increasing anthropogenic CO_2, requiring the remotely sensed NPP record to be as long as possible. The earliest remotely sensed global NPP can be traced back to year of 1982 derived from the AVHRR/NOAA instrument.

Approach to generating the measurement

The algorithm of the MODIS GPP/NPP is based upon the original logic proposed by Monteith that NPP under non-stressed conditions is linearly related to the amount of absorbed Photosynthetically Active Radiation (PAR). The growth of vegetation in the real world is subject to a variety of stresses tending to reduce the potential growth rate, especially as a result of low temperatures and the availability of both solar radiation and water. There is also a cost associated with the growth and maintenance of vegetation, termed as autotrophic respiration. With accounting for the stresses and respiration, the algorithm calculates daily GPP using follow equation,

$$GPP = PAR * FPAR * \varepsilon \quad (1)$$

where ε is light use efficiency. $FPAR$ is the fraction of absorbed PAR, and PAR accounts for about 45% of surface downward solar radiation,

$$PAR = S\downarrow_s * 0.45 \quad (2)$$

and ε is the reduction of the potential, $\varepsilon_{\max}$, resulting from low temperature (T_f) and water availability (VPD_f),

$$\varepsilon = \varepsilon_{\max} * T_f * VPD_f \quad (3)$$

Daily $PsnNet$ is the remainder of GPP subtracted by the maintenance respiration by leaves and roots (R_{m_lr}),

$$PsnNet = GPP - R_{m\_lr} \quad (4)$$

Assuming growth respiration is about 25% of NPP, annual NPP can be computed as

$$NPP = 0.8 * \sum_{i=1}^{365} (PsnNet - R_{m\_w}) \quad (5)$$

where R_{m_w} is maintenance respiration by live-wood. All maintenance respiration terms are calculated according to Q_{10} theory, which is temperature dependent.

After MODIS GPP/NPP data started to be operationally provided in early 2000, intensive validation and sensitivity analyses of the data and the algorithm, including these from historical AVHRR data, have allowed for the improvements of the algorithm, and optimization of parameters involved. As a result, we have determined that these data are now sufficiently mature to be used in a wide variety of applications.

The three upstream products for inputs of the algorithm are MODIS land cover, 8-day MODIS FPAR/LAI (Lead Area Index), and daily coarse resolution meteorological reanalysis data set, DAO/NASA (now GMAO/NASA - the Global Modeling and Assimilation Office belonging to NASA). The two MODIS input data sets are standard MODIS operational products, and in 2006, GMAO plans to reprocess their reanalysis data set with a new assimilation system, GEOS5.0, which will have more accuracy relative to previous versions.

NPP is the annually accumulated daily fixed carbon by vegetation, which makes it unique relative to other weekly, bi-weekly or monthly remotely sensed products, because any missing or contaminated daily remotely sensed data will lead to an incomplete and less useful estimate of NPP. Our study has shown that over most tropic rain forests, roughly 80% of 8-day FPAR/LAI are contaminated due to severe and frequent cloudiness. As a result, there is a need to reprocess MODIS GPP/NPP to fill the periods with missing and contaminations at the end of each acquisition year to provide complete annual products.

The MODIS GPP/NPP is sensitive to meteorological data sets and different FPAR/LAI data sets. Therefore, calibration of the parameters in look-up-table is critical to offset the error from the input, in order to generate a reliable global GPP/NPP data set. Also more validation is needed to evaluate the accuracy and reliability of the data set. These validation work needs to expend to others areas outside of North America, such as east Asian, where monsoons lead to large inter-annual variability in weather patterns, and human activities have large impacts on land surface process.

The results from validation of MODIS GPP at sites of flux network are promising. Direct comparison of MODIS annual GPP (MOD17A3) with observations for 37 site-years has resulted in a higher correlation and lower bias (r=0.855, relative error=19%) than MODIS annual GPP calculated using tower meteorology (r=0.792, relative error=-2%). Overall, the arithmetic mean difference between DAO and tower meteorology based GPP results is 28% ± 45%, indicating that the DAO meteorology plays an important role in the accuracy of the GPP algorithm, and that this role is site-specific. The sensitivity study at the global scale by replacing DAO meteorological data input with ERA-40 and NCEP/NCAR reanalysis, and by comparison these meteorological reanalysis data with the observations from weather stations, reveals that the degree of uncertainty is regional dependent and the largest uncertainties occur in tropic regions. To account for the uncertainties from meteorological data set, we will also generate MODIS GPP/NPP with NCEP/NCAR as a driver in place of the DAO meteorology.

Intended sources for the measurement

Instrument of MODIS from both TERRA and AQUA will be used to generate a GPP/NPP data set, and TERRA will be the primary platform to be used because it provides two more years of data than AQUA. In addition, historical data acquired by AVHRR/NOAA can also be used to build an NPP record as early as 1982. In the future, after TERRA is out of commission, the next generation of instruments, NPOESS/VIIRS, will be the primary instrument to continue creation of the global GPP/NPP data set. Other instruments, such as SPOT-VEGETATION can be used as an alternative data source to generate GPP/NPP if both MODIS and VIIRS fail.

For validation work, *in situ* carbon flux measurements are required at stations within the eddy flux tower networks. Other ancillary measurements are also needed, such as daily weather and seasonal LAI, in order to derive GPP and NPP at stand level for validation and refinement of the algorithm.

Necessary supporting activities, tasks

The degree of usefulness of the data is largely dependent on the accuracy and consistency of the input data sets, especially the daily meteorological data set. Currently, the official MODIS GPP/NPP is generated with DAO as an input, and during the 5 years of operation (2000~2005), the system for meteorological assimilation by DAO has been updated 3 times (GEOS400, GEOS402 and GEOS403). These changes in DAO version pose inconsistency of GPP/NPP data set, resulting in unreliable data both in magnitude and inter-annual variability. Therefore, consistent DAO data are required for the

consistency of long term MODIS GPP/NPP data. Of course, other input data sets, such as land cover, FPAR/LAI should also be consistent.

Relationships to other products and programs

The MODIS GPP/NPP product is part of the NASA EOS project, and it also makes a significant contribution to other large international and regional projects, such as the Global Carbon Project (GCP), the Global Terrestrial Observing System (GTOS), the North American Carbon Program (NACP), and the European Carbon Project (CarboEurope), among others. GCP is responding to the challenge of quantification of global carbon balance through a shared partnership between the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP), whose scientific goal is to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them. GTOS was co-established by UNEP, FAO, UNESCO, the International Council of Scientific Unions (ICSU), and the World Meteorological Organization (WMO), which was created in response to international calls for a deeper understanding of global change in the Earth System. NACP is a plan for carbon cycle research focused on measuring and understanding sources and sinks of CO_2, CH_4, and CO in North America and adjacent oceans. It was developed as a component of the U.S. Interagency Carbon Cycle Science Program and as a contribution to U.S. climate change research planning. CarboEurope is to understand and quantify the present terrestrial carbon balance of Europe and the associated uncertainty at local, regional and continental scales.

Key references

Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, 300: 1560-1563.

Running, S., R. R. Nemani, F. A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto. 2004. A continuous satellite-derived measure of global terrestrial primary production. *BioScience*, 54(6): 547-560.

Zhao, M., F. A. Heinsch, R. R. Nemani, S. W. Running. 2005. Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sensing of Environment*, 95(2): 164-176.

Zhao, M., S. W. Running, R. R. Nemani. 2006. Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. *Journal of Geophysical Research*, 111: G01002, doi:10.1029/2004JG000004.

Heinsch, F. A., M. Zhao, S. W. Running, J. S. Kimball, R. R. Nemani, K. J. Davis, et al. 2006. Evaluation of remote sensing based terrestrial productivity from MODIS using tower eddy flux network observations. *IEEE Transactions on Geoscience and Remote Sensing*, in press.